

[0031] The accelerated beam 54 then enters a long narrow drift tube 56 with a typical diameter less than about 5 mm and a typical length of about 10 cm. A cone shaped neutron generating target 42, preferably made of titanium is mounted in the end of drift tube 56. Drift tube 56 may be formed of spaced concentric outer tubing 57 and inner tubing 58, which define a coolant flow channel 59 therebetween. Water or other coolant is flowed into coolant channel 59 through inlet 61 and removed through outlet 62. As shown in FIG. 3B, a pair of spacers 63 divide the channel 59 into an inlet channel 64 and outlet channel 65 so that coolant can be flowed along the length of the drift tube 56. FIG. 3C shows the details of the tip of drift tube 56 with the target 42 mounted therein, with the coolant channel 59 passing around the tip. FIG. 3D shows an alternate single tube structure for drift tube 56, in which cooling is done by a cooling channel 60 at the junction of drift tube 56 with the acceleration column 50.

[0032] Target 42 has a cone shaped surface 43 which receives the ion beam 54 and becomes loaded with deuterium or a mixture of deuterium and tritium. Ion beam 54 is sufficiently nondiverging so that the beam strikes target 54 without substantial loss of ions from the drift tube 56. The conical surface 43 of target 42 provides larger surface area for capturing the incident ions. Neutrons are produced on the target surface by D-D or D-T fusion reactions. If the beam current is 1 mA, the D-D neutron flux will be 10^8 n/s and the D-T neutron flux will be 10^{10} n/s.

[0033] FIGS. 4A, B are ion optics computation results using the IGUN simulation code for double or single gap accelerators. The results show that the ion beam can propagate into the target without impinging on the inner wall of the drift tube. The beam spreads to about 2 mm diameter when it arrives at the cone shaped target and the power density is much reduced. The heat load of about 100 W on the target will be removed by circulating water. Either of the two water cooling schemes shown above can be used, i.e. the double layer tubing arrangement of FIGS. 3A-C or the edge cooling arrangement of FIG. 3D.

[0034] The neutron generator 40 is well suited for brachytherapy since the tip of drift tube 56 with neutron generating target 42 can be inserted in direct contact with the tissues being treated by inserting the tube 56 as a catheter. The neutron source can be readily turned on and off as needed to deliver the desired dosage by simply turning the ion source 44 on and off by applying suitable pulses of RF to antenna 47. The Ti target 42 and drift tube 56 are biased at ground potential while the plasma source 44 (or the first electrode 52 of acceleration column 50) is biased at +100 kV relative to ground. The plasma source and accelerator column are both shielded with a grounded casing (not shown). Thus the part of the instrument in contact with the patient is always at ground potential and therefore will post no high voltage danger during therapy treatment.

[0035] FIG. 5 illustrates another sealed tube neutron generator 70 of the invention that is based on a RF driven plasma ion source 71 with external antenna 72. Ion source 71 is formed of a quartz (or other suitable material, e.g. ceramic) chamber 73 with antenna (coil) 72 wound externally thereon. Antenna 72 is connected through matching network 74 to RF generator 75 for producing a plasma in chamber 73. While ion sources 10, 40 previously described

are generally miniaturized because of their medical applications, ion source 71 may be of any size, depending on the application, e.g. about 10 cm diameter; however, the principles of operation are similar.

[0036] For neutron generation, the plasma is a deuterium or deuterium and tritium (or even just tritium) plasma. The ion source can be operated at several mTorr of deuterium or tritium or a mixture thereof. The low pressure operation enables the design of the accelerator column for high voltage (e.g. 120 kV) standoff.

[0037] Ions from plasma chamber 73 are extracted through plasma electrode 76, which has a large aperture 77 (e.g. >3 cm diameter) which is subdivided into a plurality of smaller apertures 78 (e.g. 2 mm diameter). This multi-beamlet design provides large extraction area with high current density, e.g. 100 mA/cm² or higher) and high atomic ion species (e.g. >90%).

[0038] The accelerator column 79 is a single gap column with the neutron generating target 80 forms the second or extraction electrode. Neutron generating target 80 has a conical or tapered inner surface 82 oriented along the beam axis to provide a large target area for the ion beam. FIG. 6 shows a calculated ion beam distribution along a target surface. Target 80 is preferably made of titanium and becomes loaded with deuterium and/or tritium so that neutrons are generated by D-D or D-t (or even T-T) reactions. The length and slope of the conical surface 82 can be tailored to minimize the beam deposition power density. Cooling channels 83 can also be included in target 80 for removing heat. Since the length of the target 80 can be extended, generator 70 can provide a line source of neutrons.

[0039] The ion source 71 can be operated at high voltage and the target 80 at ground potential, e.g. plasma chamber 73 and plasma electrode 76 are shown connected to a high voltage supply (H.V.). Target 80 is enclosed in a metal housing 84, and connected thereto by mount 86. Housing 84 is separated from HV by insulator 85, and is preferably grounded. Alternatively the ion source can be grounded and target 80 at high voltage. Housing 84 can also be surrounded by shield 87.

[0040] This embodiment of the invention can produce D-D neutron flux higher than 10^{11} n/s with modest length and diameter. D-T neutron output is about two orders of magnitude higher. This neutron generator can form a line source with low beam power density and high neutron flux. This configuration has particular application for cargo or luggage screening and for reactor start-up.

[0041] Changes and modifications in the specifically described embodiments can be carried out without departing from the scope of the invention which is intended to be limited only by the scope of the appended claims.

1. A neutron generator including an electrical ground connected to a neutron generating target, said neutron generator comprising:

a plasma chamber disposed in a plasma ion source and an external RF antenna disposed outside and around said plasma chamber;

an extraction and acceleration system including three electrodes, a first electrode having a centered aperture being disposed at an end of said plasma chamber for